

$H^\pm \rightarrow cb$ in models with two or more Higgs doublets

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Searches for light H^\pm s via $t \rightarrow H^\pm b$ are being carried out at the LHC. Herein, it is normally assumed that the dominant decay channels are $H^\pm \rightarrow \tau \nu$ and $H^\pm \rightarrow cs$ and separate data analyses are performed with comparable sensitivity to the underlying model assumptions. However, the $H^\pm \rightarrow cb$ decay rate can be as large as 80% in models with two or more Higgs doublets with natural flavour conservation, while satisfying the constraint from $b \rightarrow s\gamma$ for $m_{H^\pm} < m_t$. Despite the current search strategy for $H^\pm \rightarrow cs$ is also sensitive to $H^\pm \rightarrow cb$, a significant gain in sensitivity could be obtained by tagging the b quark from the decay $H^\pm \rightarrow cb$.

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1. Introduction

At the Large Hadron Collider (LHC), if $m_{H^\pm} < m_t$, H^\pm states would mostly [1] be produced in $t \rightarrow H^\pm b$ decays [2]. Searches in this channel are being performed by the LHC experiments, assuming the decay modes $H^\pm \rightarrow cs$ and $H^\pm \rightarrow \tau\nu$. Since no signal has been observed, constraints are obtained on the parameter space of a variety of models, chiefly 2-Higgs Doublet Models (2HDMs) [3]. Searches in these channels so far carried out at the LHC include: 1) $H^\pm \rightarrow cs$ with 4.7 fb^{-1} by ATLAS [4] and with 19.7 fb^{-1} by CMS [5]; 2) $H^\pm \rightarrow \tau\nu$ with 19.5 fb^{-1} by ATLAS [6] and with 19.7 fb^{-1} by CMS [7]. Although the current limits on $H^\pm \rightarrow cs$ can be applied to the decay $H^\pm \rightarrow cb$ as well (as discussed in [8] in the Tevatron context), a further improvement in sensitivity to $t \rightarrow H^\pm b$ with $H^\pm \rightarrow cb$ could be obtained by tagging the b quark which originates from H^\pm [8, 9, 10].

We will estimate the increase in sensitivity to $\text{BR}(H^\pm \rightarrow cb)$ in a specific scenario, for definiteness, a 3-Higgs Doublet Model (3HDM) (see, e.g. [11])¹. Reasons to consider a 3HDM could be the following: 1) the existence already of 3 generations of quarks and leptons; 2) (scalar) dark matter (in presence of inert Higgs doublets) and a non-SM like sector.

2. Charged Higgs bosons in the 3HDM

We will consider here the ‘democratic’ 3HDM [11] wherein the fermionic states u, d, ℓ obtain mass from v_u, v_d, v_ℓ (the three different Vacuum Expectation Values (VEVs)), respectively. The mass matrix of the charged scalars is diagonalised by the 3×3 matrix unitary U :

$$\begin{pmatrix} G^+ \\ H_2^+ \\ H_3^+ \end{pmatrix} = U \begin{pmatrix} \phi_d^+ \\ \phi_u^+ \\ \phi_\ell^+ \end{pmatrix}. \quad (2.1)$$

Henceforth, we will assume H_2^\pm to be the lightest state and relabel it as H^\pm .

The Yukawa couplings of the H^\pm in a 3HDM are given through the following Lagrangian

$$\mathcal{L}_{H^\pm} = - \left\{ \frac{\sqrt{2}V_{ud}}{v} \bar{u} (m_d X P_R + m_u Y P_L) d H^+ + \frac{\sqrt{2}m_e}{v} Z \bar{\nu}_L \ell_R H^+ + H.c. \right\}. \quad (2.2)$$

In a 3HDM, X, Y and Z are defined in terms of the matrix elements of U ,

$$X = \frac{U_{12}}{U_{11}}, \quad Y = -\frac{U_{22}}{U_{21}}, \quad Z = \frac{U_{32}}{U_{31}}, \quad (2.3)$$

and are mildly constrained from the theoretical side, as the unitarity of U leads to the relation

$$|X|^2 |U_{11}|^2 + |Y|^2 |U_{12}|^2 + |Z|^2 |U_{13}|^2 = 1. \quad (2.4)$$

¹As explained in [12], in the Aligned Two Higgs Doublet Model (A2HDM) [13] one can also have a large $\text{BR}(H^\pm \rightarrow cb)$ [10] with $m_{H^\pm} < m_t$, so that our numerical results for the 3HDM apply directly to the A2HDM too. In contrast, while large values of $\text{BR}(H^\pm \rightarrow cb)$ are also possible in the so called Type III 2HDM [8, 14, 15], they only occur for $m_{H^\pm} > m_t$ due to the constraints from $b \rightarrow s\gamma$ requiring $m_{H^\pm} > 300 \text{ GeV}$ [16, 17, 18]. Finally, in the three other versions of the 2HDM (Type I, II and IV), in which $\text{BR}(H^\pm \rightarrow \tau\nu)$ and $\text{BR}(H^\pm \rightarrow cs)$ dominate, one has that $\text{BR}(H^\pm \rightarrow cb)$ is always $< 1\%$ (due to a small V_{cb}).

Hence, the magnitudes of X, Y and Z cannot all be simultaneously less or more than 1. This is due to the fact that all three VEVs cannot be simultaneously large or small, as $v_d^2 + v_u^2 + v_\ell^2 = (246 \text{ GeV})^2$. Further theory constraints can be imposed via the usual requirements of VV scattering unitarity ($V = W^\pm$ or Z), perturbativity, vacuum stability, positivity of mass eigenstates and of the Hessian, Electro-Weak Symmetry Breaking (EWSB) (now in presence of an $m_h = 125 \text{ GeV}$ SM-like Higgs boson), etc. (see [19, 20, 21] for details), though all these primarily affect the neutral Higgs sector of a 3HDM.

Indeed, are the phenomenological constraints those which impinge greatly on the allowed values of X, Y and (less so) Z . The main limits come from the following low energy processes:

- $Z \rightarrow b\bar{b}$: $|Y| < 0.72 + 0.24 \left(\frac{m_{H^\pm}}{100 \text{ GeV}} \right)$;
- $b \rightarrow s\gamma$: $-1.1 < \text{Re}(XY^*) < 0.7$, e.g. for $m_{H^\pm} = 100 \text{ GeV}$.

In essence, in the democratic 3HDM H^\pm can be light since XY^* is arbitrary. As for LHC constraints enforced by the Higgs boson search (and coupling measurements), these are rather loose as the H^\pm state only enters via loop effects (e.g. in $\gamma\gamma$ and $Z\gamma$ decays).

3. Results

In the light of the previous discussion, a distinctive signal of the H^\pm boson from a 3HDM would then be a large $\text{BR}(H^\pm \rightarrow cb)$ with the charged Higgs boson emerging from an (anti)top decay (since $m_{H^\pm} < m_t$). The necessary condition for this is: $|X| \gg |Y|, |Z|$. (In the numerical analysis we fix $m_{H^\pm} = 120 \text{ GeV}$ and $|Z| = 0.1$.) We illustrate in Fig. 1 the $\text{BR}(H^\pm \rightarrow cb)$ and $\text{BR}(H^\pm \rightarrow cs)$ in a 3HDM. Over the strip between the lines $|XY^*| = 0.7$ and 1.1 (notice that this area does not correspond to the entire region surviving $b \rightarrow s\gamma$ constraints), it is clear the predominance of the former over the latter.

As mentioned, both ATLAS and CMS have searched for $t \rightarrow H^\pm b$ and $H^\pm \rightarrow cs$. The procedure is simple. Top quarks are produced in pairs via $q\bar{q}, gg \rightarrow t\bar{t}$. One (anti)top then decays via $t/\bar{t} \rightarrow Wb$, with $W \rightarrow e\nu$ or $\mu\nu$. The other (anti)top decays via $t/\bar{t} \rightarrow H^\pm b$. Hence, $H^\pm \rightarrow cs$ gives two (non- b quark) jets. Candidate signal events are therefore $b\bar{b}e\nu$ plus two non- b jets. A peak at m_{H^\pm} in the invariant mass distribution of non- b jets is the hallmark signal. The main background comes from $t/\bar{t} \rightarrow Wb$ and $W \rightarrow ud/cs$, which would give a peak at m_{W^\pm} .

We simply remark here that applying a third b -tag would improve sensitivity to $H^\pm \rightarrow cb$ greatly, as the main background from $W \rightarrow cb$ has a very small rate. This is made explicit by choosing a b -tagging efficiency $\varepsilon_b = 0.5$, a c -quark mistagging rate $\varepsilon_c = 0.1$ and a light quark (u, d, s) mistagging rate $\varepsilon_j = 0.01$. It follows that the estimate gain in sensitivity is then:

$$\frac{[S/\sqrt{B}]_{\text{btag}}}{[S/\sqrt{B}]_{\text{tag}}} \sim \frac{\varepsilon_b \sqrt{2}}{\sqrt{(\varepsilon_j + \varepsilon_c)}} \sim 2.13. \quad (3.1)$$

Current ATLAS and CMS limits for $m_{H^\pm} = 120 \text{ GeV}$ are of order $\text{BR}(t \rightarrow H^\pm b) < 0.02$ (assuming $\text{BR}(H^\pm \rightarrow cs) = 100\%$). In the plane of $[|X|, |Y|]$ we now show contours of: 1) $\text{BR}(t \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow cb + cs)$; 2) $\text{BR}(t \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow cb)$. This is done in Fig. 2, from where it is clearly visible that constraints from $t \rightarrow H^\pm b$ are competitive with those from $b \rightarrow s\gamma$. In fact,

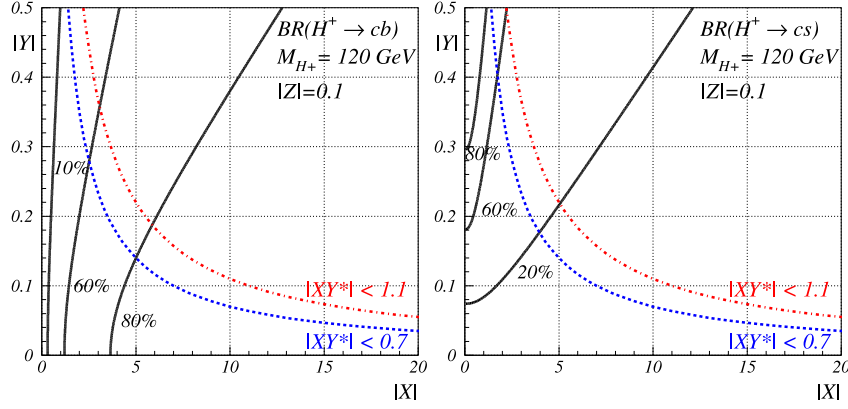


Figure 1: Left: $BR(H^\pm \rightarrow cb)$ in the plane $[|X|, |Y|]$. Right: $BR(H^\pm \rightarrow cs)$ over the same plane.

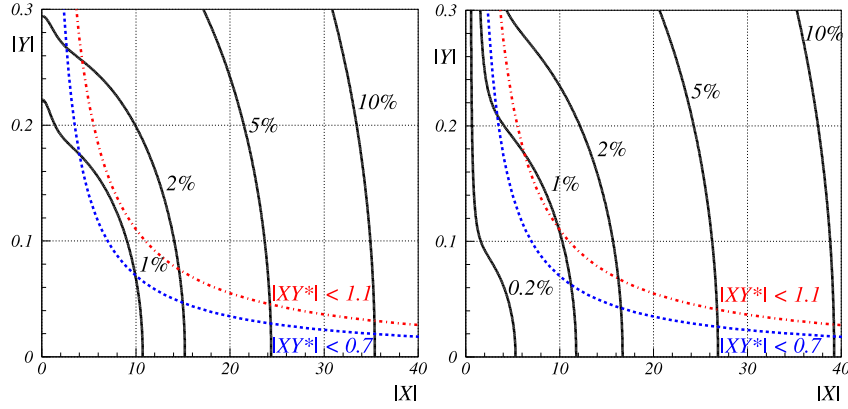


Figure 2: Left: $BR(t \rightarrow H^\pm b) \times BR(H^\pm \rightarrow cb + cs)$ (no b -tag). Right: $BR(t \rightarrow H^\pm b) \times BR(H^\pm \rightarrow cb)$ (b -tag).

$BR(t \rightarrow H^\pm b) < 2\%$ rules out two regions which cannot be excluded via $b \rightarrow s\gamma$: 1) $15 < |X| < 40$ and $0 < |Y| < 0.04$; 2) $0 < |X| < 4$ and $0.3 > |Y| > 0.8$. Further, tagging the b -quark from $H^\pm \rightarrow cb$ would possibly allow sensitivity to $BR(t \rightarrow H^\pm b) < 0.5\%$ or less so that $t \rightarrow H^\pm b$ combined with $H^\pm \rightarrow cb$ could provide even stronger constraints on the $[|X|, |Y|]$ plane (or perhaps enable discovering $H^\pm \rightarrow cb$).

4. Conclusions

A Higgs particle has been discovered, maybe there are more such states to be found, including a H^\pm . We have emphasised here that a light (with mass below m_t) H^\pm is possible in a 3HDM wherein $H^\pm \rightarrow cb$ can be dominant. Based on ongoing analyses by ATLAS and CMS searching for $t \rightarrow H^\pm b$, $H^\pm \rightarrow cs$, which are already sensitive to $H^\pm \rightarrow cb$, we proposed tagging the b -quark from $H^\pm \rightarrow cb$, procedure that could further improve sensitivity to the fermionic couplings of H^\pm (X and Y). This is a straightforward extension of ongoing searches for $t \rightarrow H^\pm b$ and $H^\pm \rightarrow cs$ that would enable one to make rather definitive statements regarding the viability of a 3HDM (and also a A2HDM).

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